New force and the LHC

Hye-Sung Lee
(Brookhaven National Lab)

The University of Texas ARLINGTON™

Colloquium at the UT-Arlington
April 14, 2010

Long title:

Why a New force should be discovered at the LHC, and what we can do with it

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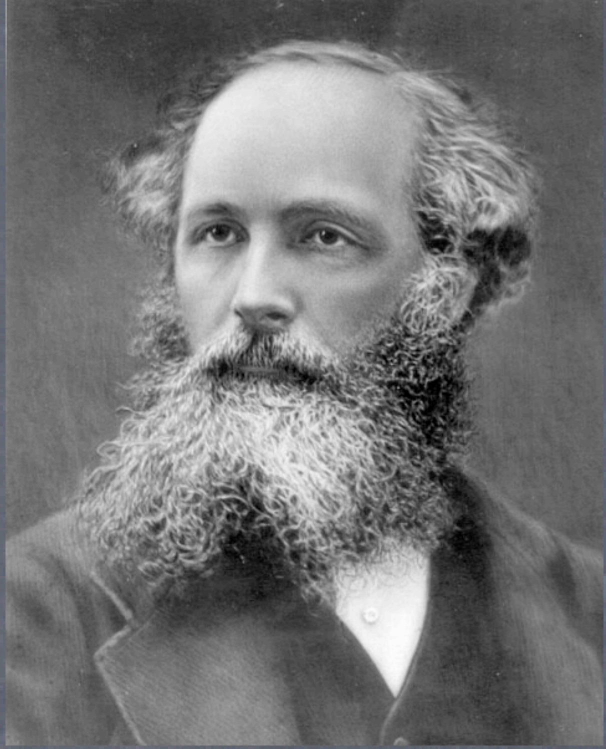

$$F = ma$$

Fundamental forces known to us:

(1) Gravity [I. Newton, ... in 17C]

(2) Electromagnetic force [J. Maxwell, ... in 19C]

(3) Weak nuclear force [S. Weinberg, ... in 20C]

(4) Strong nuclear force [M. Gell-Mann, ... in 20C]

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"Where do we go from here?"

$$F = ma$$

F… …mental forces known to us:

(1) … in 17C]

(2) Electromag… …axwell, … in 19C]

(3) Weak nuclear force [S. W…

(4) Strong nuclear force [M. Gell-Mann, … …C]

Option 1. Try to "unify" all forces.

Option 2. Try to find "another" force.

"Where do we go from here?"

5th force

: my topic today!

Physics is not Lotto.

We need a **motivation** to search for a New force.

Outline

1. Why Supersymmetry?

   : Brief overview of particle physics

2. Supersymmetry calls for a New force

   : Motivation of a New gauge symmetry

3. What can we do with a New force at LHC?

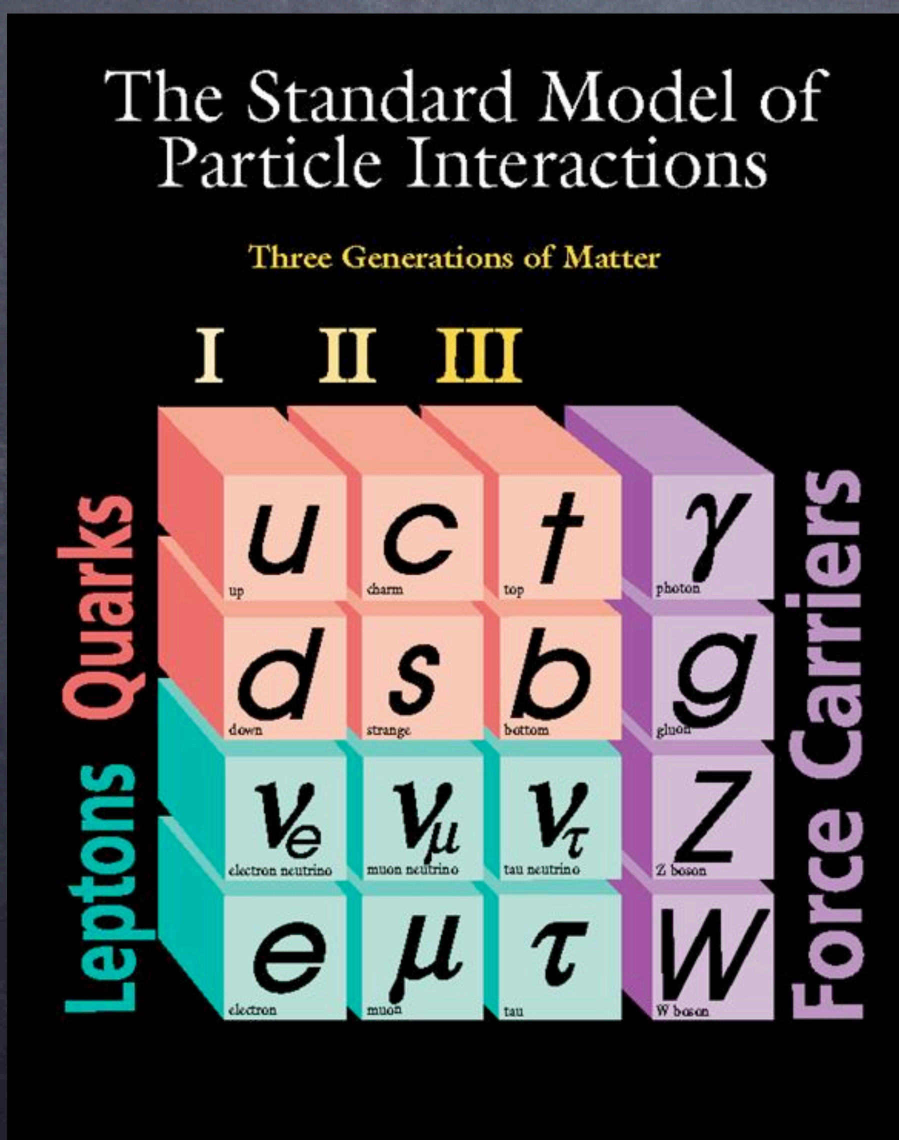
   : Overview of my LHC research

The motivation
of 5th force

1. Why Supersymmetry?

Standard Model (SM)

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (g), Z/W



Gauge symmetry = SU(3) x SU(2) x U(1)
(All known forces except for Gravity)

No gravity in SM

$$F = G_N \frac{Mm}{r^2}$$

$G_N=10^{-10}$ [MKS] --> Neglect Gravity.
(SM is valid up to $r \approx 10^{-35}$ m)

Standard Model (SM)

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
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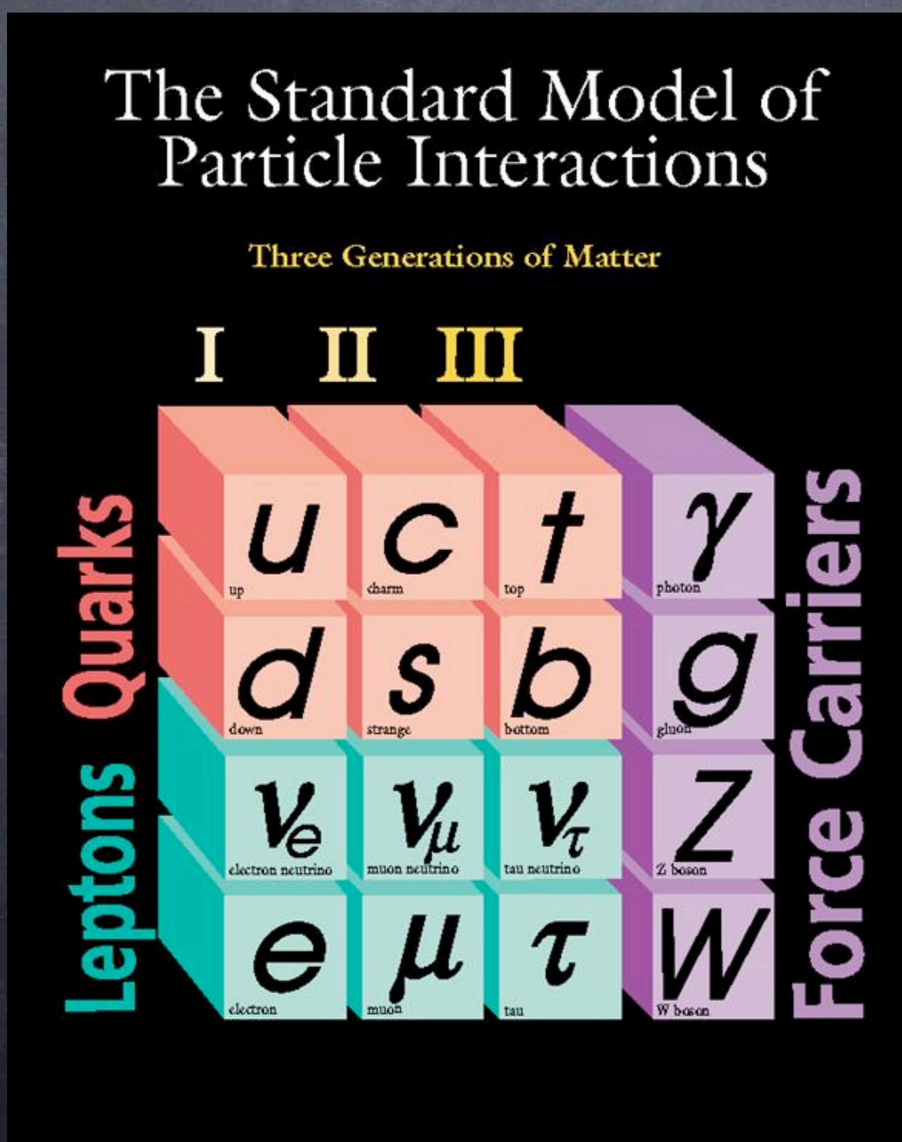

Gauge symmetry = SU(3) x SU(2) x U(1)

(All known forces except for Gravity)

Strong force

Weak force

EM force

Standard Model (SM)

Spin 0	"Scalar"	Higgs (H)
Spin 1/2	"Fermions"	Quarks (Q), Leptons (L)
Spin 1	"Gauge bosons"	Photon (γ), Gluon (g), Z/W

Gauge symmetry = SU(3) x SU(2) x U(1)
(All known forces except for Gravity)

Higgs: the only undiscovered particle and
the only scalar (spin 0) particle.

Higgs scalar can explain the masses of the fermions and gauge bosons (otherwise, massless).

Standard Model (SM)

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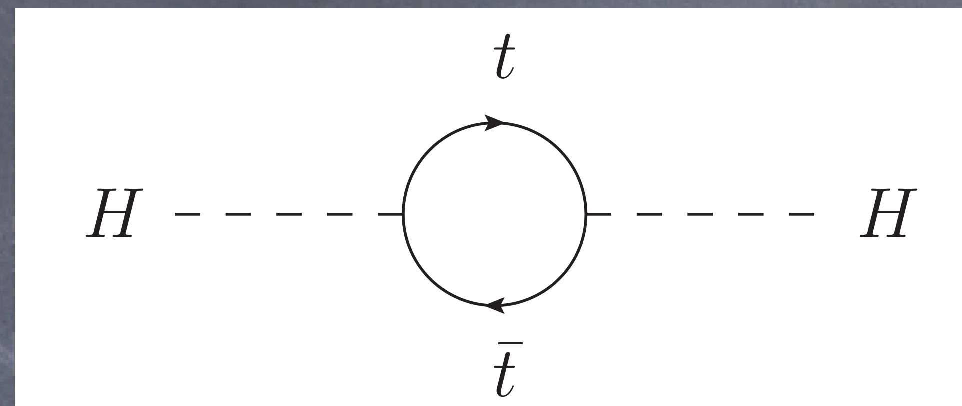
Higgs: the only undiscovered particle and
the only scalar (spin 0) p

Major discovery goal at LHC

Higgs scalar can explain the masses of the fermions and gauge bosons (otherwise, massless).

Higgs is a solution and a problem

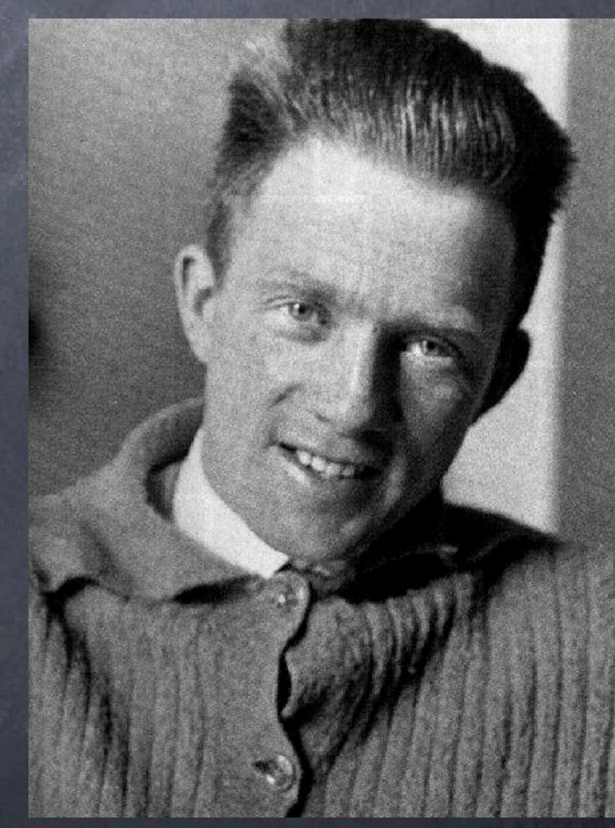


Quantum correction to Higgs mass :

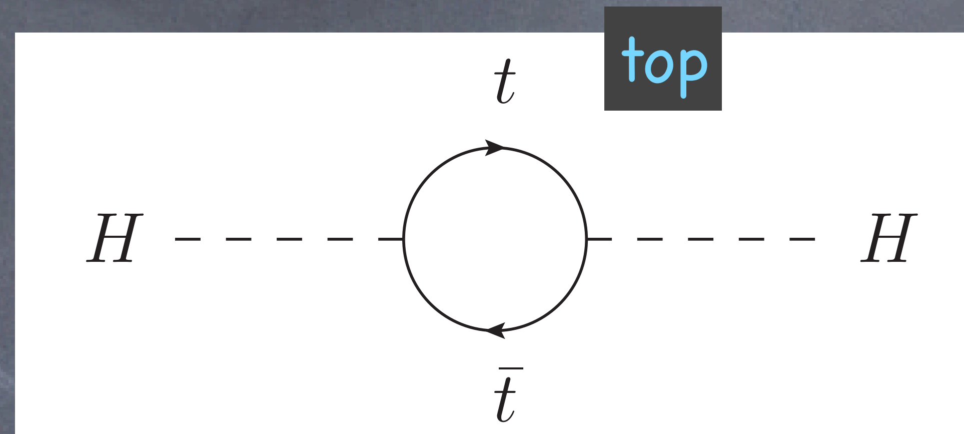
- Higgs borrows ENERGY for a short TIME and returns.
- It contributes to the Higgs mass.

Heisenberg's
Uncertainty Principle

$$\Delta E \Delta t \gtrsim \frac{\hbar}{2}$$



Higgs is a solution and a problem



$$\delta m_H^2(\text{top}) = -\Lambda^2 + \cdots$$ (Λ=cutoff scale of theory)

= 10^{19} GeV

(SM valid up to 10^{-35} m)

$$m^2_{H_{\text{physical}}} = m^2_{H_0} + \delta m^2_H = m^2_{H_0} - (10^{19}\ \text{GeV})^2$$

Expected Higgs mass = O(10^{19} GeV)

But, physical Higgs mass should be O(100 GeV)

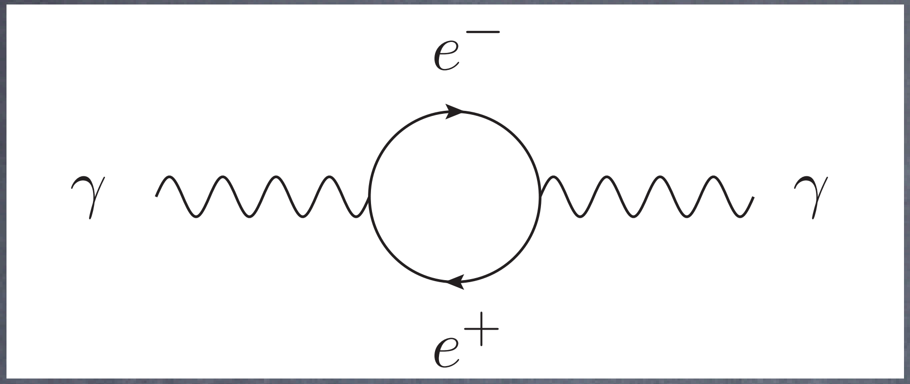
[Hierarchy problem]: Divergence (Λ^2) in scalar mass^2

Something is missing.

(Proton mass ≈ 1 GeV)

What about other particles?

- Spin 1 particle (gauge boson):

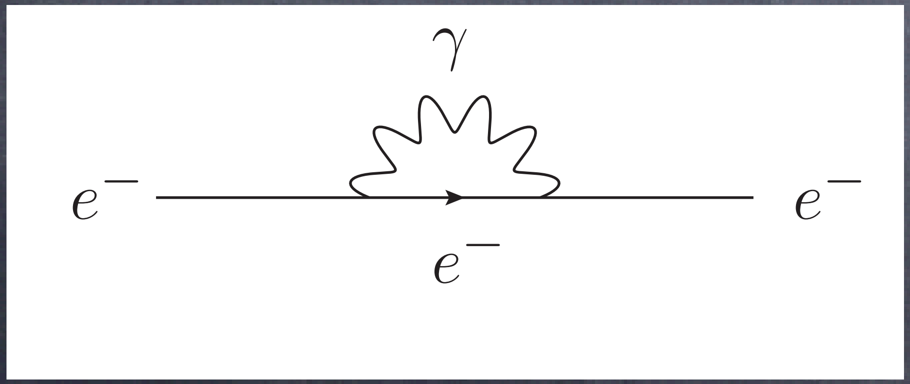


= 0

OK!

"Spin 1 particle mass is protected by gauge symmetry."

- Spin 1/2 particle (fermion):



= (very small)

OK!

"Spin 1/2 particle mass is protected by chiral symmetry."

Look for a new symmetry to protect spin 0 particle (Higgs scalar) mass.

Supersymmetry (SUSY)

SUSY: fermion (spin 1/2) <--> boson (spin 0, 1)

SUSY predicts "Superpartners (or SUSY particles)" (same quantum number except for spin).

Spin 0	Higgs (H)	Spin 1/2	Higgsino ($\tilde{H}$)
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark ($\tilde{Q}$), Slepton ($\tilde{L}$)
Spin 1	γ, g, Z/W	Spin 1/2	$\tilde{\gamma}$, $\tilde{g}$, $\tilde{Z}/\tilde{W}$

[SM particles] [SUSY particles]

Supersymmetry (SUSY)

SUSY: fermion (spin 1/2) <--> boson (spin 0, 1)

SUSY predicts "Superpartners (or SUSY particles)"
(same quantum number except for spin).

Provides Dark Matter candidate

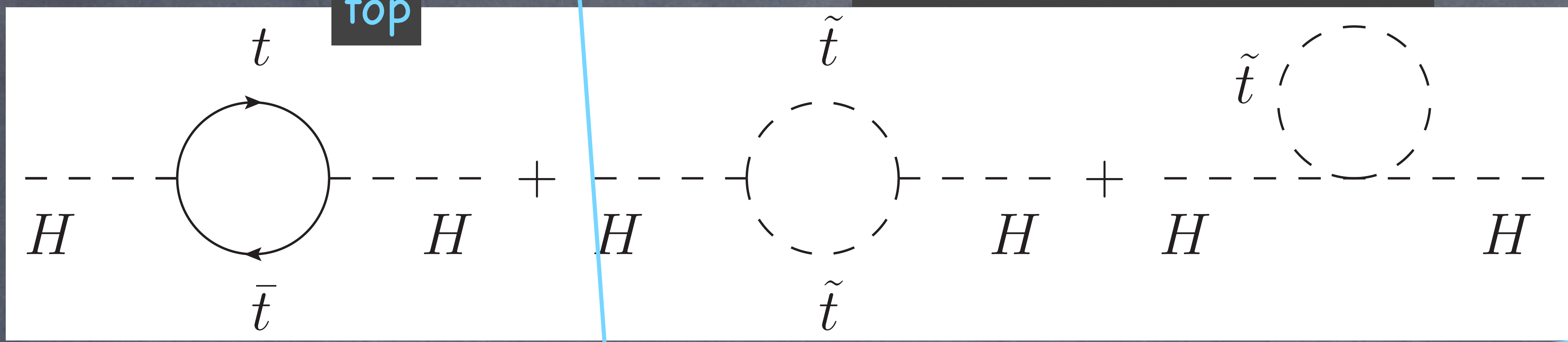
Spin 0	Higgs (H)	Spin 1/2	[illegible] (H)
Spin 1/2	Quark (Q), Lepton (L)	Spin 0	Squark ($\tilde{Q}$), Slepton ($\tilde{L}$)
Spin 1	γ, g, Z/W	Spin 1/2	$\tilde{\gamma}$, $\tilde{g}$, $\tilde{Z}/\tilde{W}$

[SM particles] [SUSY particles]

Higgs problem motivates Supersymmetry

scalar top (Superpartner)

top



SM part

SUSY part

$$\begin{aligned}\delta m_H^2(\mathrm{top}+\mathrm{stop}) &= (-\Lambda^2+\cdots)+(\Lambda^2+\cdots)\\ &= -m_{\tilde{t}}^2\log(\Lambda/m_{\tilde{t}})+\cdots\end{aligned}$$

OK!

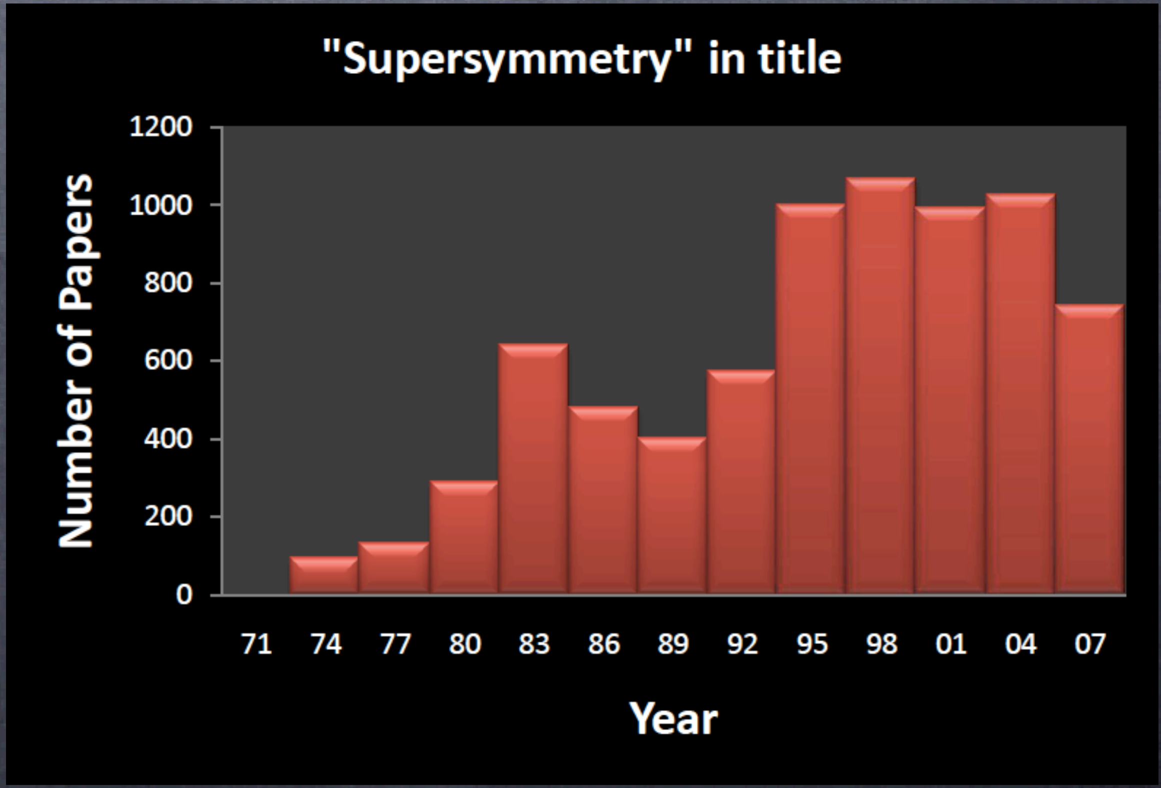
Divergence (Λ^2) cancelled!

"Spin 0 particle (Higgs scalar) mass can be protected by Supersymmetry."

Supersymmetry in literature

Although there are other ideas ...

SPIRES database search results	
"Supersymmetry" in title	7400 papers
"Higgs" in title	9000 papers



Supersymmetry in literature

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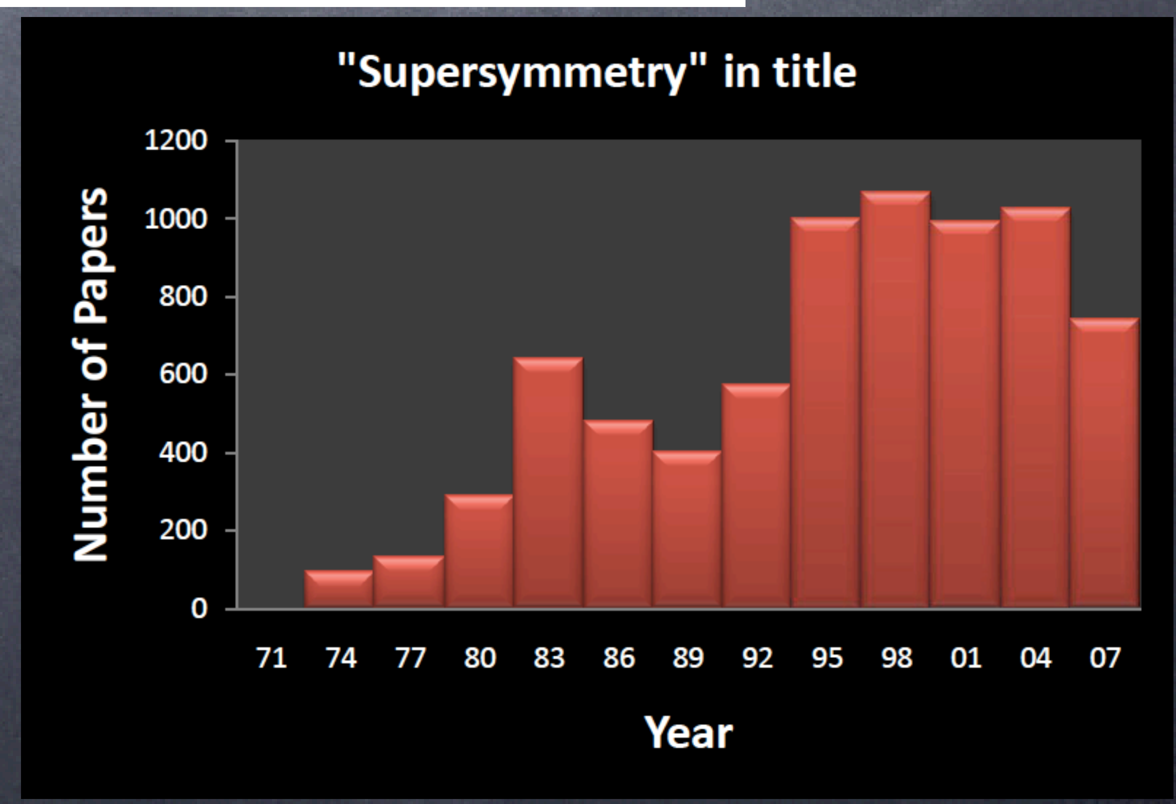
Another major discovery goal at LHC

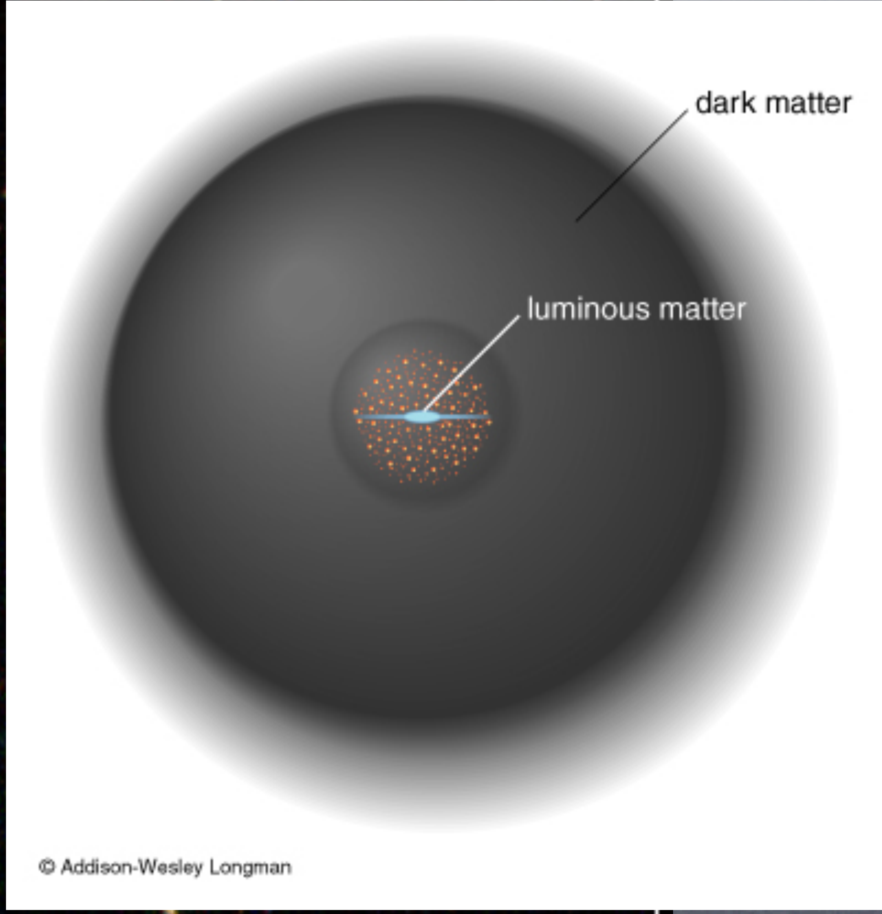


2. Supersymmetry calls for a New force

Naive implementation

$\boxed{\text{Standard Model + Supersymmetry ?}}$

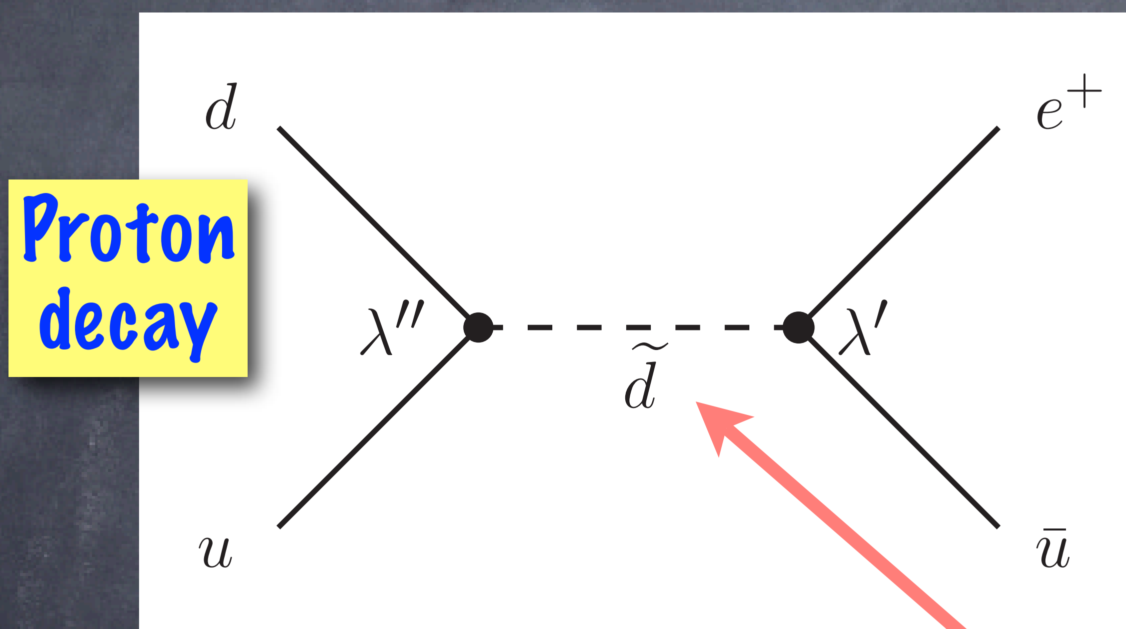
--> There are some Problems.

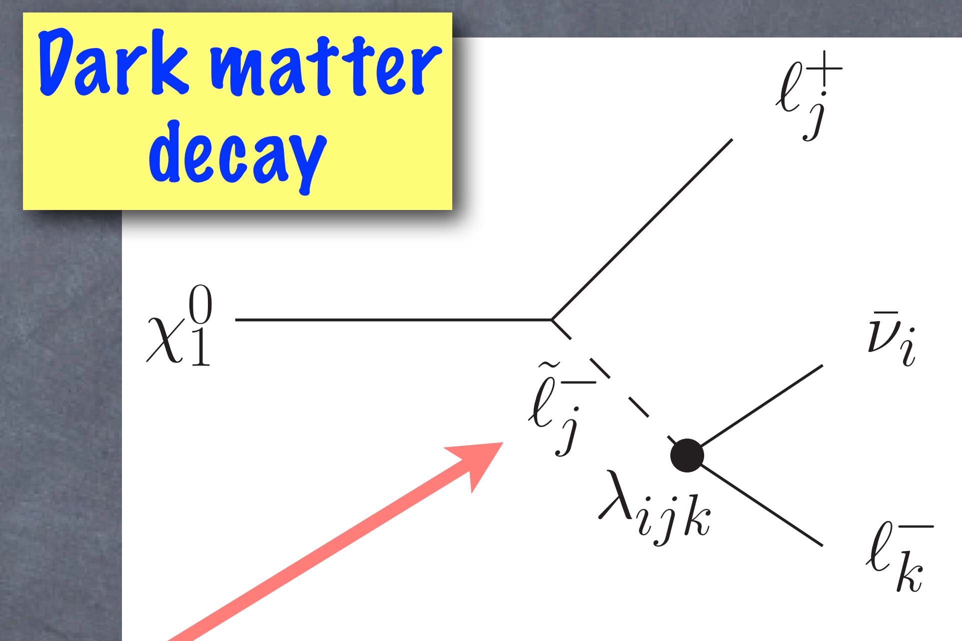


Universe = Bright world + Dark world
(Proton, etc) (Dark matter)

Building-blocks of Universe
(should be stable)

Building-blocks decay fast under Supersymmetry





SUSY particles

Supersymmetry makes “Proton” and “Dark matter candidate” decay too fast.

We need something

$$\boxed{\text{Standard Model + Supersymmetry + "Something"}}$$

To address proton &
dark matter stability

It is like
we need Reins to control a Horse

We need "Something" to control Supersymmetry.
(Otherwise, building-blocks would decay fast)

Popular and old model

Standard Model + Supersymmetry + R-parity ?

Popular since it was adopted by the First Supersymmetry model (a.k.a. MSSM) [1981]

Popular and old model

Standard Model + Supersymmetry + R-parity ?

R_2 or R-parity (= SUSY particle parity)

- SM particles : even parity
- SUSY particles : odd parity

Proton : Leading order decay is forbidden

Lightest SUSY particle (LSP) : Stable DM candidate

But, R-parity is Not perfect

Some issues of the R-parity:

1. Still insufficient proton stability [Weinberg (1982)]
   [Proton still decays fast by (non-renormalizable) sub-leading order term]
2. Unnecessarily forbidden processes
   [Forbidding either Lepton # or Baryon # is enough]
3. Limited dark matter property
   [Recent cosmic data (PAMELA, Fermi) favors larger leptonic coupling]
4. Other theoretical issues
   [Other issues such as mu-problem are not addressed]

But, R-parity is Not perfect

Alternative to R-parity?

Some issues of the R-parity:

1. Still insufficient proton stability [Weinberg (1

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   [Recent cosmic data (PAMELA, Fermi) favors larger leptonic coupling]

4. Other theoretical issues

   [Other issues such as mu-problem are not addressed]

U(1)_[B-x_i L]

U(1)_[B_3]

U(1)_[U_2]

Besides, Gravity effect may explicitly break all global symmetries. [Hawking (1987)]

Even R-parity should exist only as a subgroup of a U(1) gauge symmetry.

Typically, U(1)_[B-L]

But, R-parity is Not perfect

Alternative to R-parity?

Some issues of the R-parity:

The point is

"U(1) gauge symmetry" appears to be the best candidate of "Something" to control Supersymmetry.

Even R-parity should exist only as a subgroup of a U(1) gauge symmetry.

Typically, U(1)_[B-L]

Best-motivated Supersymmetric model

New force!

Standard Model + Supersymmetry + U(1) gauge

Particles and interactions are fixed

Best-motivated Supersymmetric model

New force!

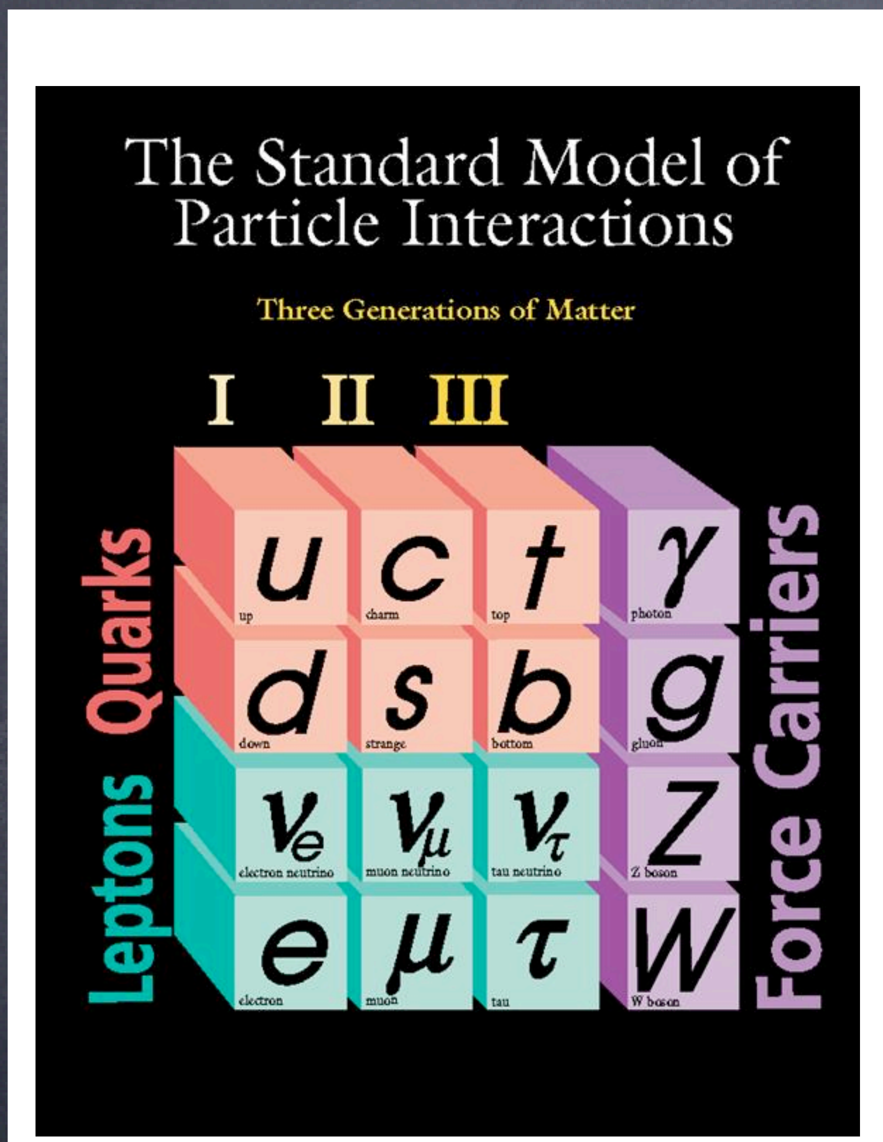
Standard Model + Supersymmetry + U(1) gauge

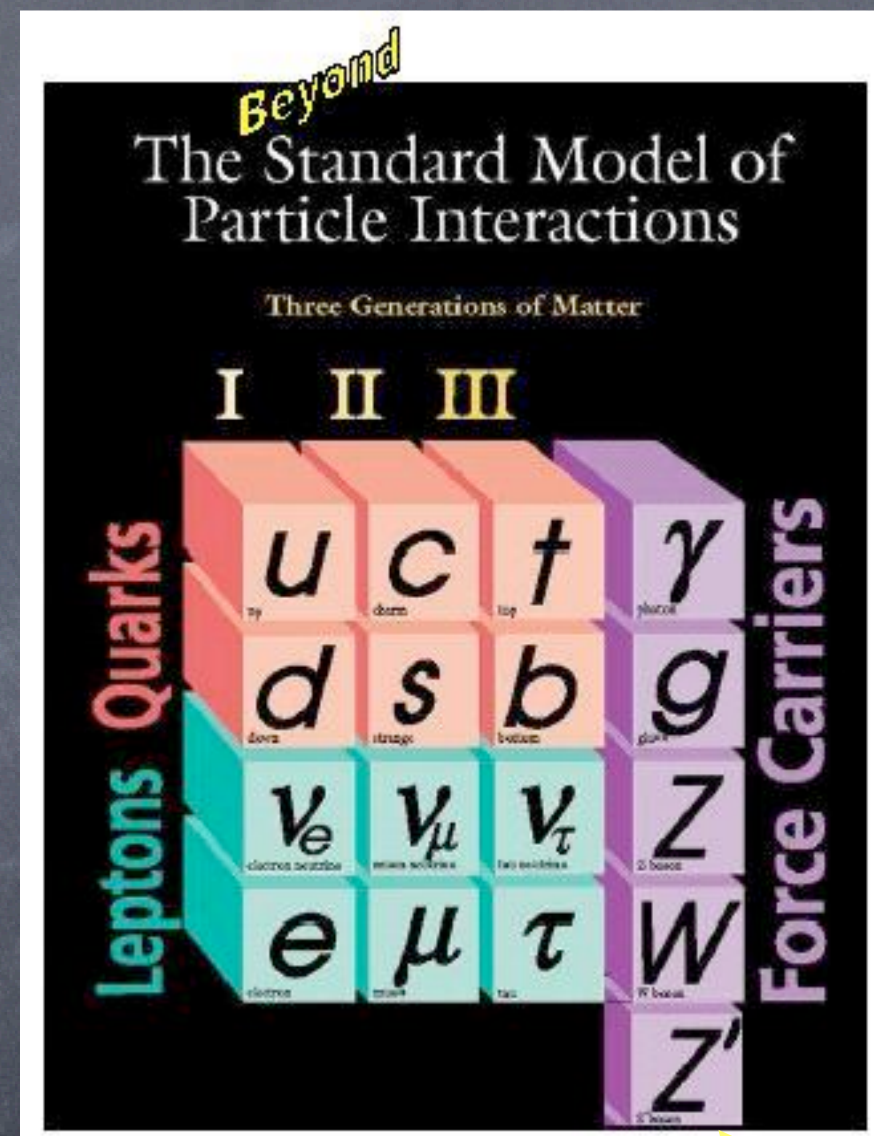
Depending on details (such as remnant discrete symmetries)

$U(1) \to Z_N$ with $Z_N = R_2, U_2, B_3, L_3, \ldots,$

many versions of Supersymmetric models can exist.

New force carrier : Z′





<u>Masses</u>

no mass

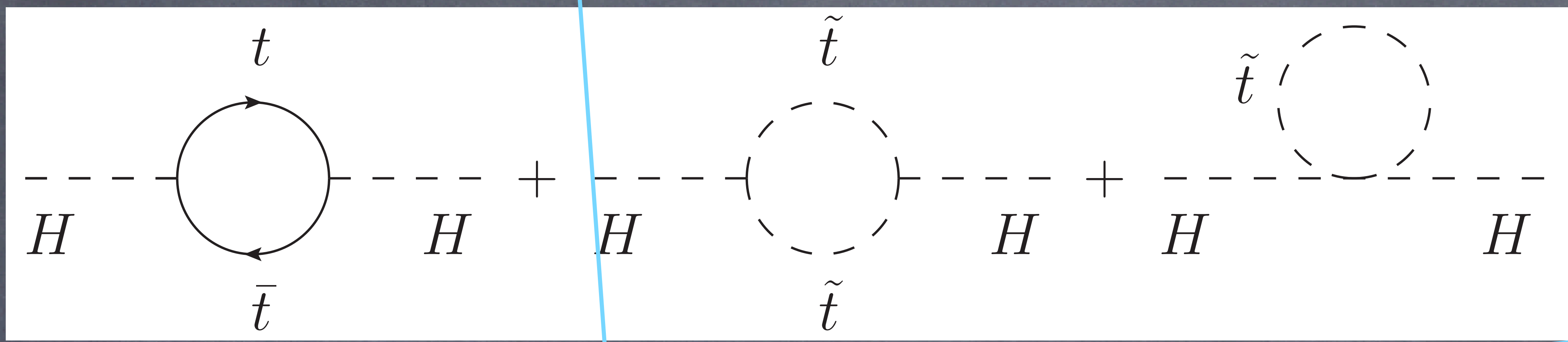
no mass

≈100 GeV

≈100 GeV

How heavy?

Superpartner mass ≈ Z′ mass



$$\delta m_H^2(\mathrm{top}+\mathrm{stop}) = (-\Lambda^2+\cdots)+(\Lambda^2+\cdots)$$
$$= -m_{\tilde t}^2\log(\Lambda/m_{\tilde t})+\cdots$$

D-term contribution to scalar masses :

$$\Delta m_{\tilde f}^2 = (\frac{2}{3}\sin^2\theta_W\cos 2\beta)\ M_Z^2 + (Q'[f]Q'[S])\ M_{Z'}^2$$

If Z′ mass >> 100 GeV

→ Superpartner mass >> 100 GeV

→ Higgs Hierarchy problem comes back!

Z′ mass "should be" O(100 GeV) ~ O(1000 GeV) !

(1 TeV = 1000 GeV)

Welcome, Large Hadron Collider!

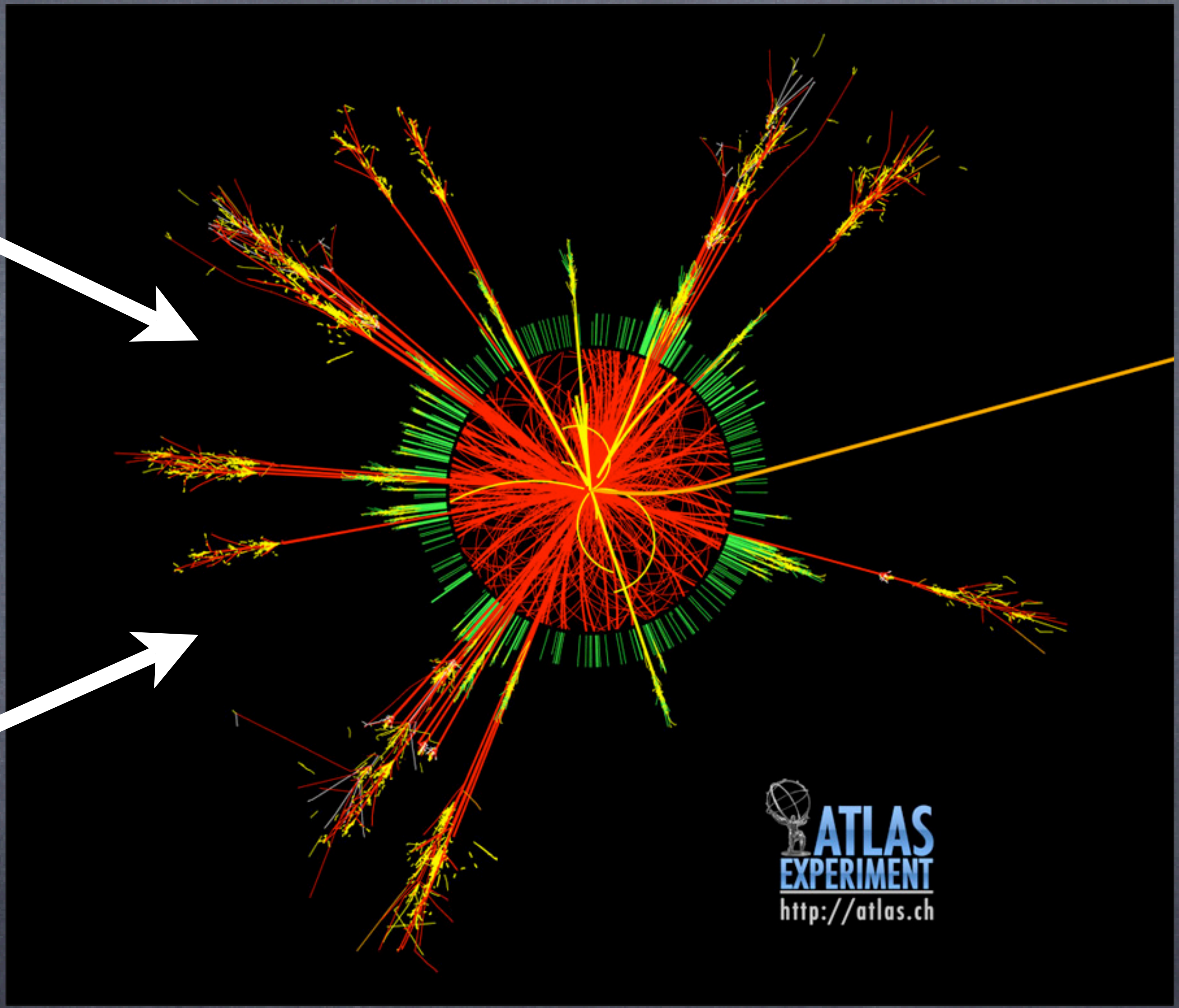
This is why the currently operating LHC
is a perfect place to hunt for Z′.

LHC (maximum energy = 14 TeV) probes a TeV scale Z′.

LHC: Proton-Proton Collider

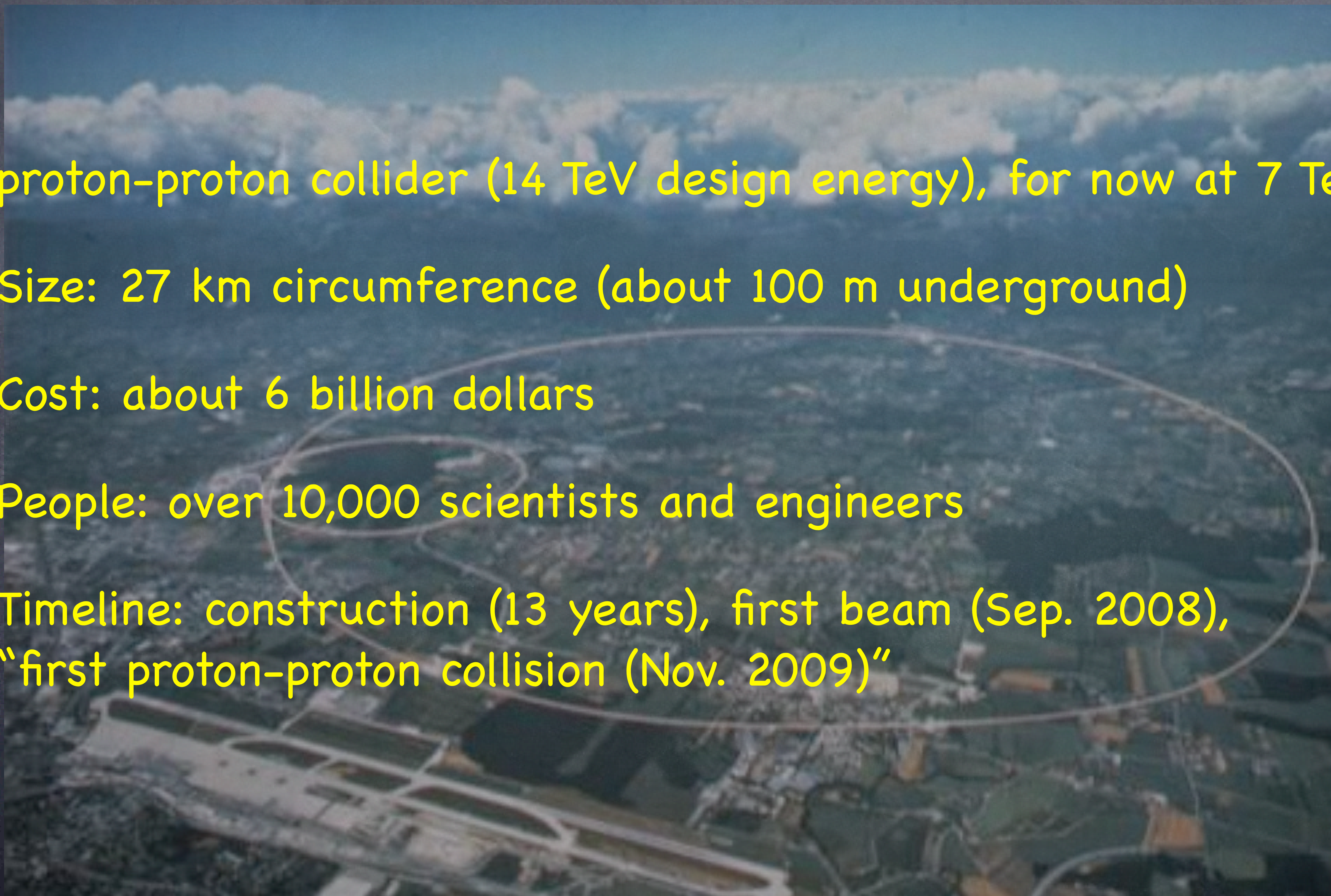
Proton
(7 TeV)

Proton
(7 TeV)



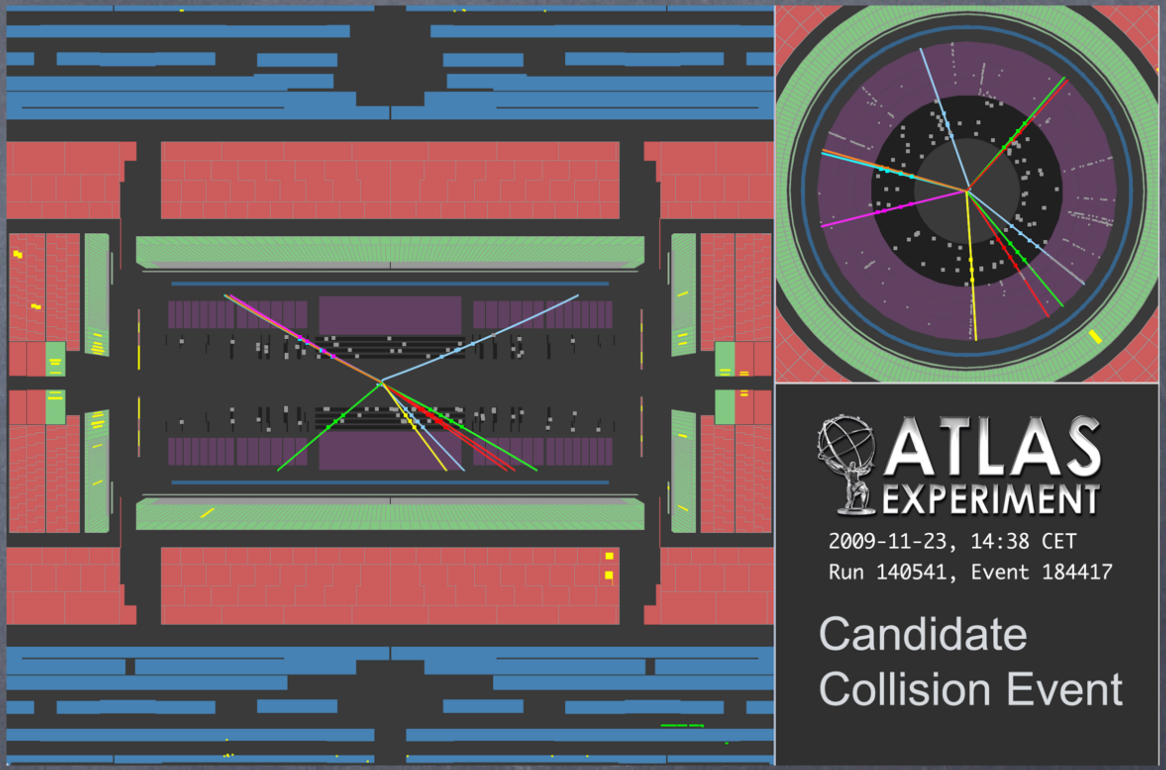
Collision reveals particle physics

Large Hadron Collider (LHC)
in Geneva, Switzerland



- proton-proton collider (14 TeV design energy), for now at 7 TeV
- Size: 27 km circumference (about 100 m underground)
- Cost: about 6 billion dollars
- People: over 10,000 scientists and engineers
- Timeline: construction (13 years), first beam (Sep. 2008), “first proton-proton collision (Nov. 2009)”

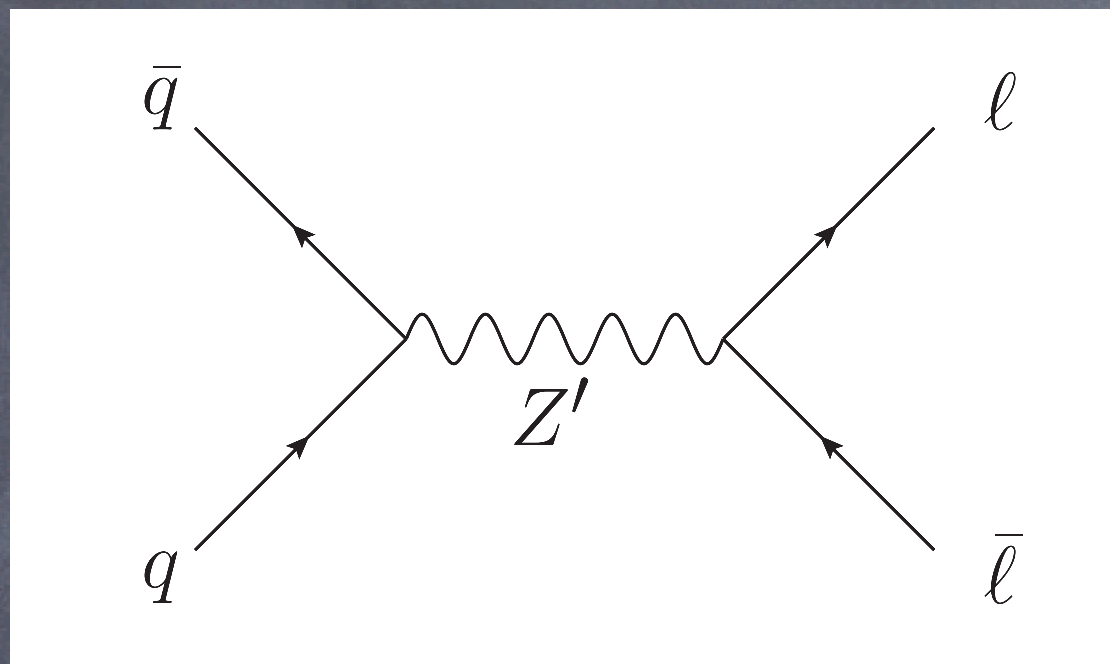
First proton-proton collision at LHC



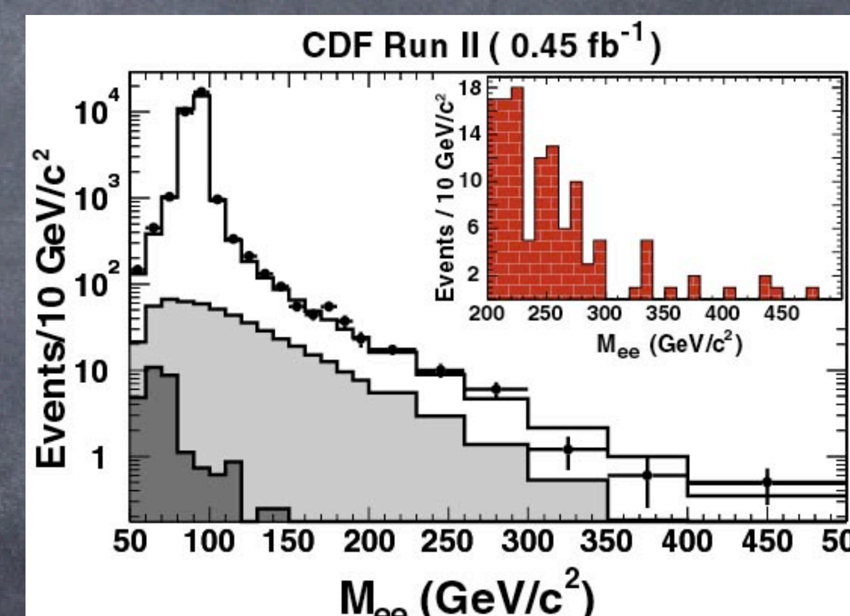
Nov. 23, 2009

Physicists experiencing a moment of *Joy* at the first collision at the LHC

Discovering Z′ at LHC



SM Z boson (91 GeV) at Tevatron



(e^+e^- or $\mu^+\mu^-$)

Dilepton Z′ resonance is very likely to be the first discovery because of
(i) enhanced cross section,
(ii) clean leptonic signal.

Expect Z′ boson at LHC

(Irreducible SM BKG for leptonic resonance is small.)

3. What can we do with a New force at LHC?

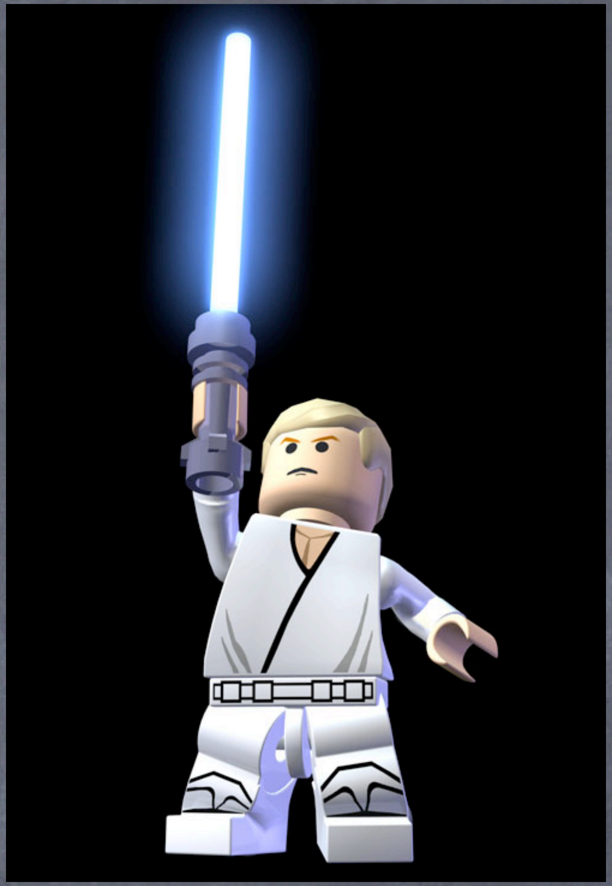
(Overview of my LHC research)

Best-motivated Supersymmetric model

Standard Model + Supersymmetry + U(1) gauge

TeV scale

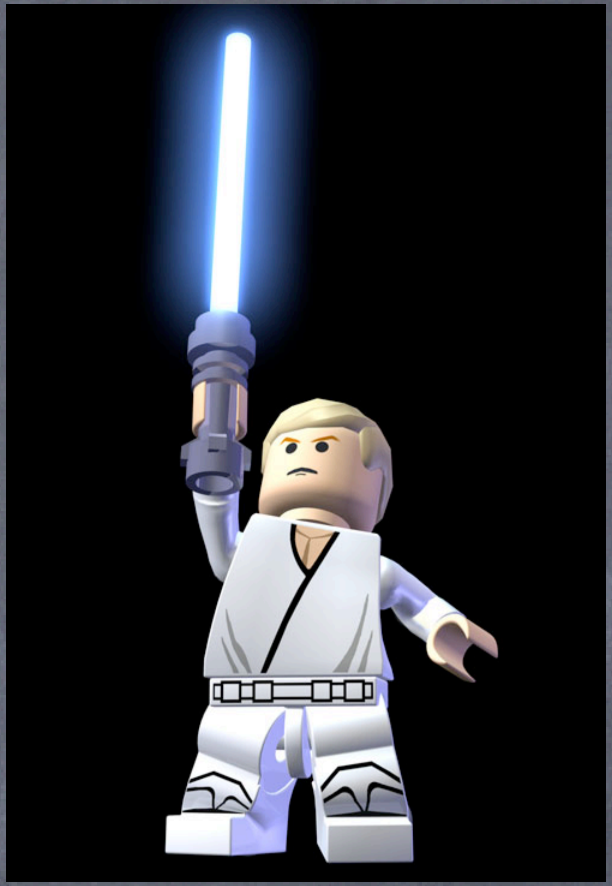
(Higgs mass ≈ Superpartner mass ≈ Z′ mass)



With a New FORCE, you can do many things.

Higgs
Dark matter
Flavor physics
"LHC phenomenology"
...

With a New FORCE, you can do many things.



Higgs
Dark matter
Flavor physics
"LHC phenomenology"
...

Re-visit old SUSY analyses with a New force.
(Get distinguishable predictions)

Our approach to LHC physics

Start

↓

Find a problem in the old SUSY model

↓

Build a new one with U(1) that can cure it

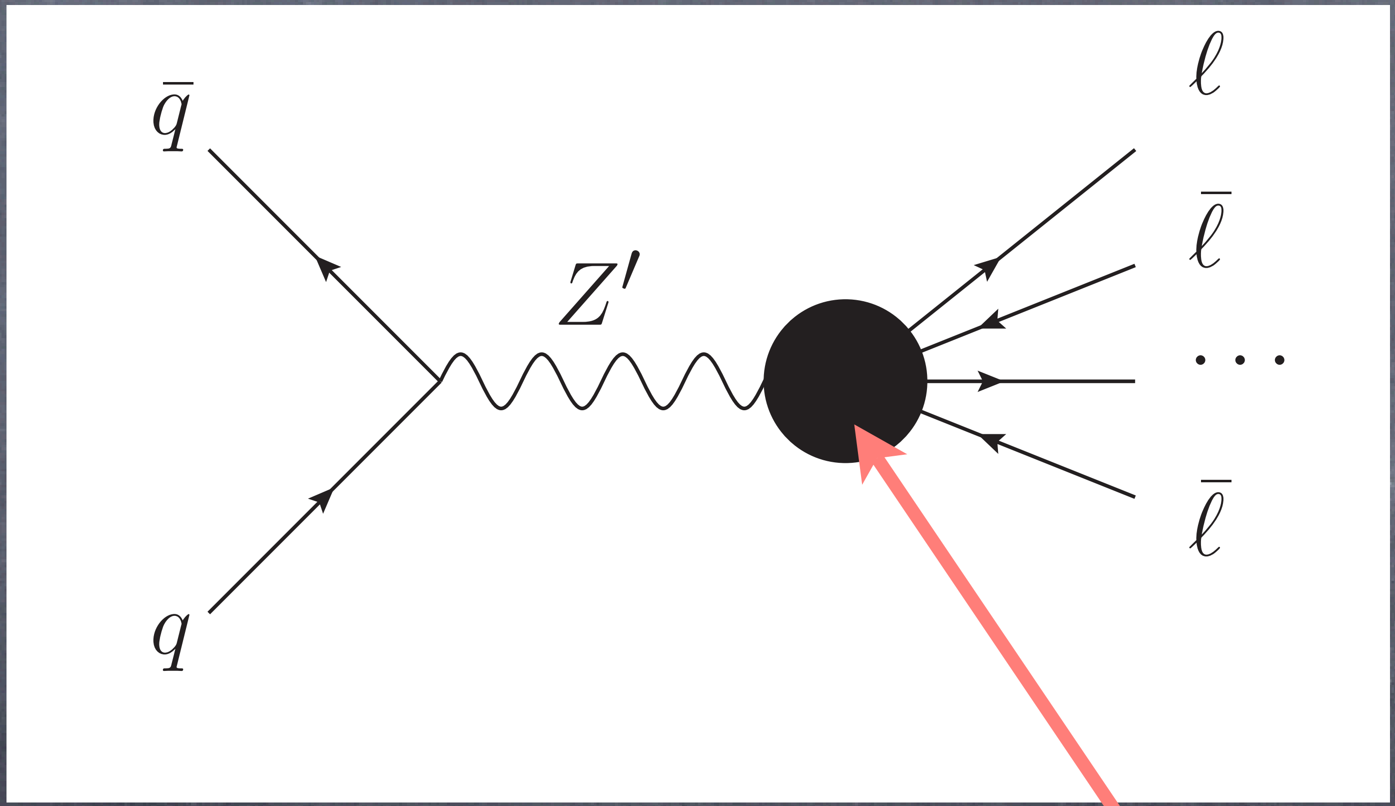
↓

Suggest novel channels for the LHC

with some MC simulations (MadGraph/MadEvent, CompHEP)

Using Z′ as a discovery tool

Specifically, we use various leptonic (e, μ)
Z′ resonances for "other new physics" search.



(flavor-dependent) 2-lepton, 4-lepton, 6-lepton, ...
Z′ resonances (at the LHC)

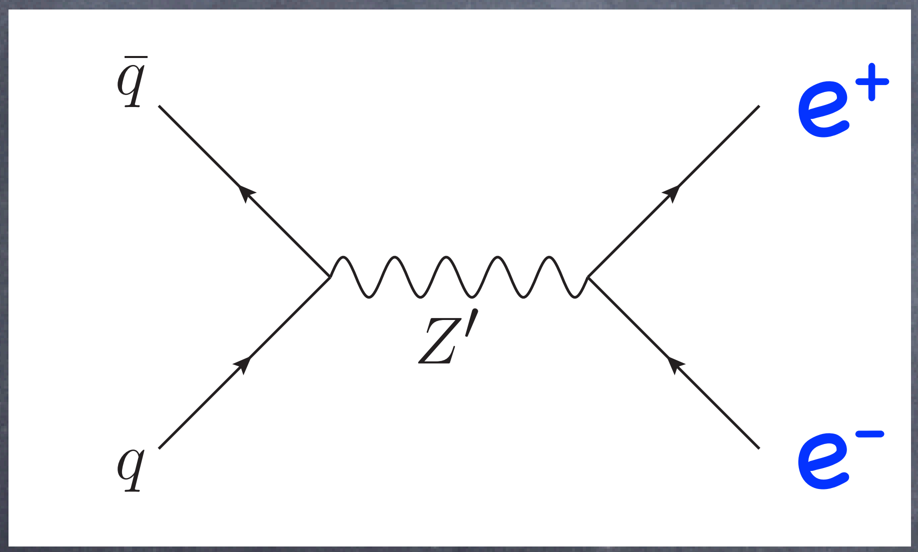
new particle
(Higgs, Superpartner)
in the middle

(i) Flavor-dependent Z′ search

2-lepton resonance

[HL, Ma (PLB 2010)]

- R-parity and U(1)_[B-L] (typically used gauge origin of R-parity)
  - Proton : Still decays fast (by non-renormalizable terms).
- Flavor-dependent gauge origin of R-parity : U(1)_[B-x_i L] (R-parity is a subgroup)
  - Proton : Sufficiently stable.
  - Character : Z' couples differently to different flavor of leptons (electron, muon, tau).



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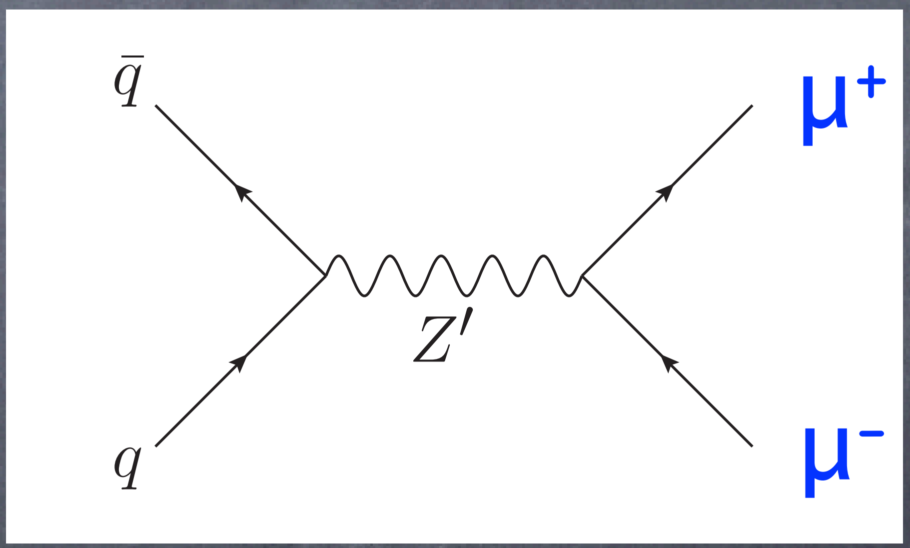
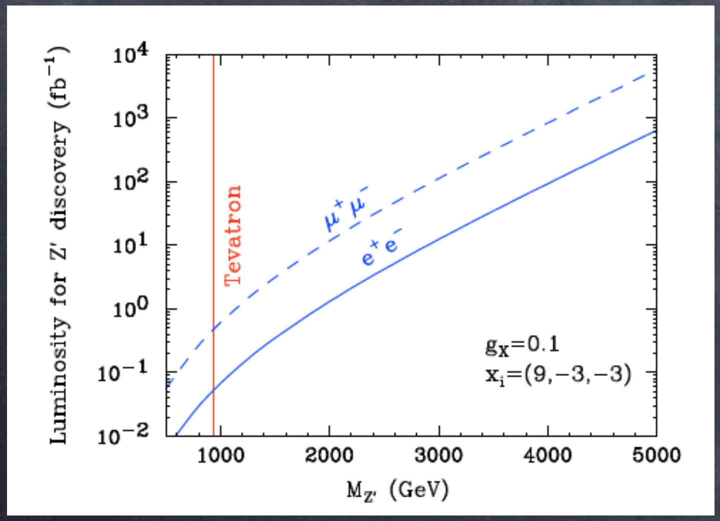




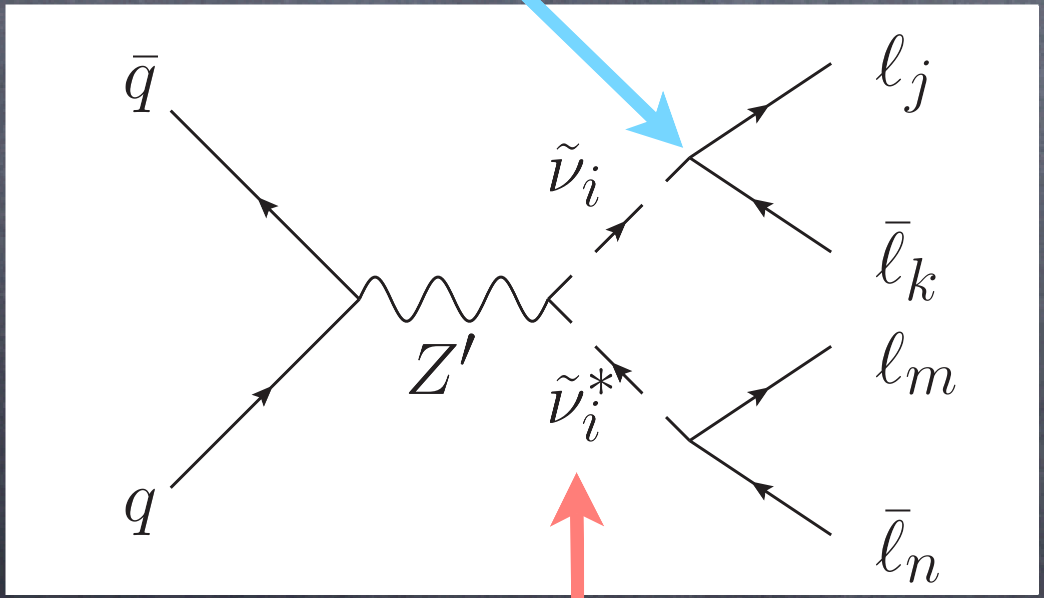
(ex) (e^+e^- events) = 9 × ($\mu^+\mu^-$ events)
with $\{x_e, x_\mu, x_\tau\} = \{9, -3, -3\}$
[Details omitted]

(ii) Supersymmetry search

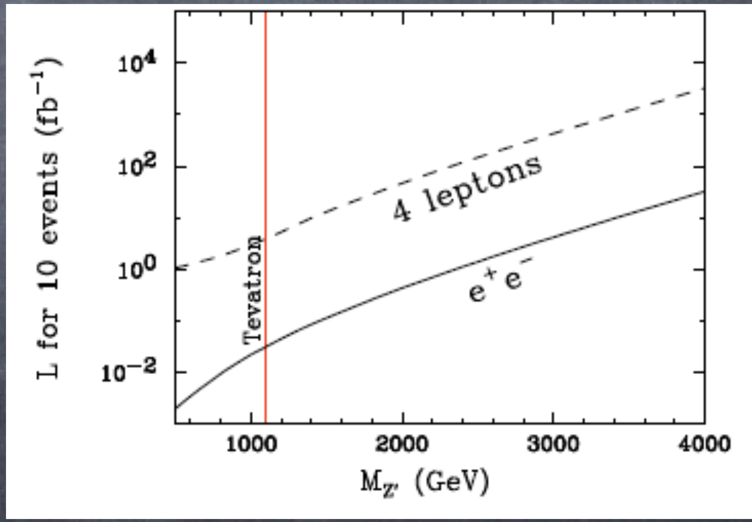
[HL, Luhn, Matchev (JHEP 2008) & HL (PLB 2009)]

4-lepton resonance

- R-parity
  - Proton : Still decays fast.
  - Character : Unnecessarily forbids both Baryon # and Lepton # violations.
- Give up R-parity : U(1)_[B_3] (B_3 is a subgroup)
  - Proton : Proton decay ($\Delta B=1$) never occurs. (selection rule of B_3 : $\Delta B=3\times$integer)
  - Character : Lepton # is freely violated.



Lightest SUSY Particle (sneutrino)



(ex) L=13 fb^{-1} for $M_{Z'}$=1500 GeV
[Details omitted]

(ii) Supersymmetry search

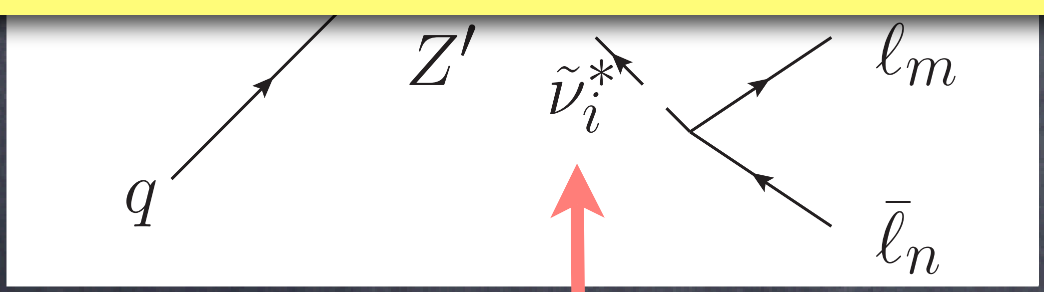
[HL, Luhn, Matchev (JHEP 2008) & HL (PLB 2009)]

4-lepton resonance

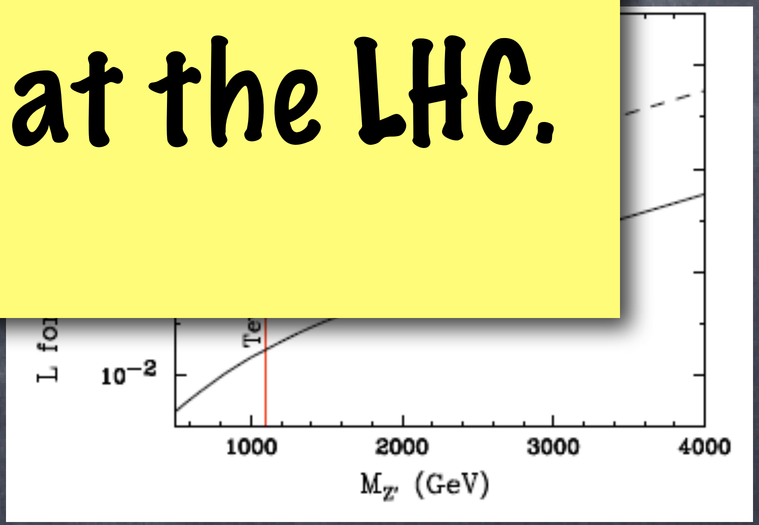
• R-pa...
• P
• C
• Give
• P
• C

The point is

New force can help "Supersymmetry search" at the LHC.



Lightest SUSY Particle
(sneutrino)



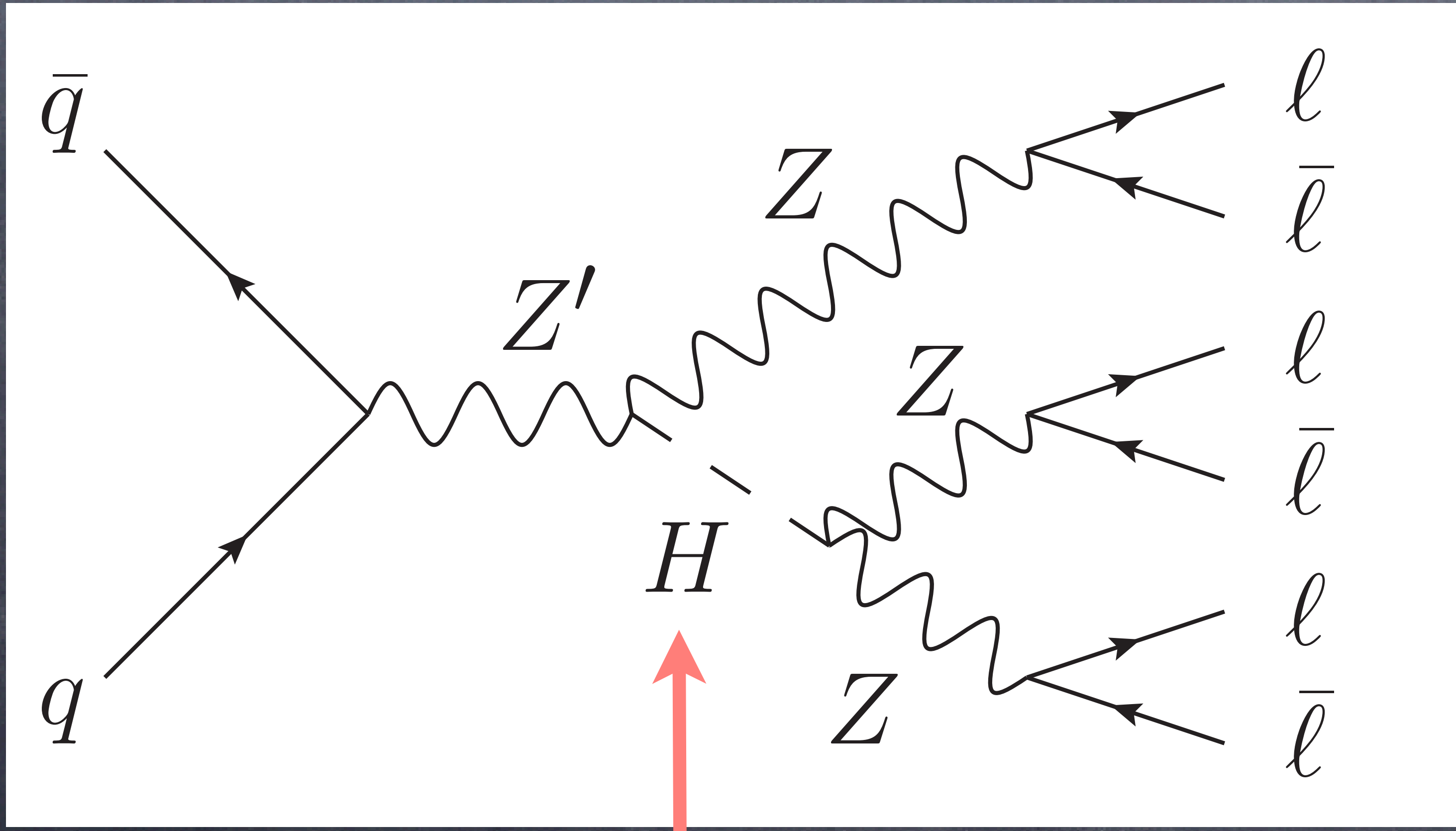
(ex) L=13 fb^{-1} for $M_{Z'}$=1500 GeV
[Details omitted]

(iii) Higgs search

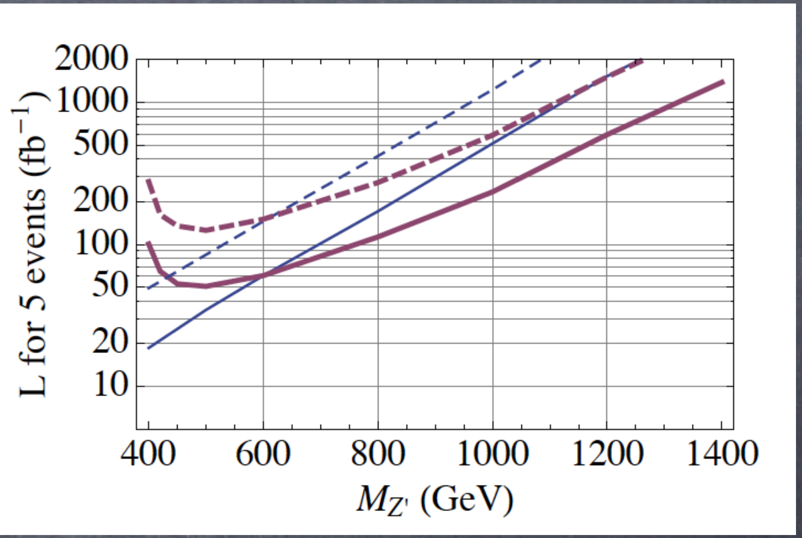
[Barger, Langacker, HL (PRL 2009)]

6-lepton resonance

- Any U(1) (The process does not need Supersymmetry)
  - Z'-Z-H coupling is sizable if Higgs doublet has U(1) charges.
  - Character : Does not require direct Z' coupling to leptons.
    (Complementary to dilepton Z' search to discover leptophobic Z')



Higgs

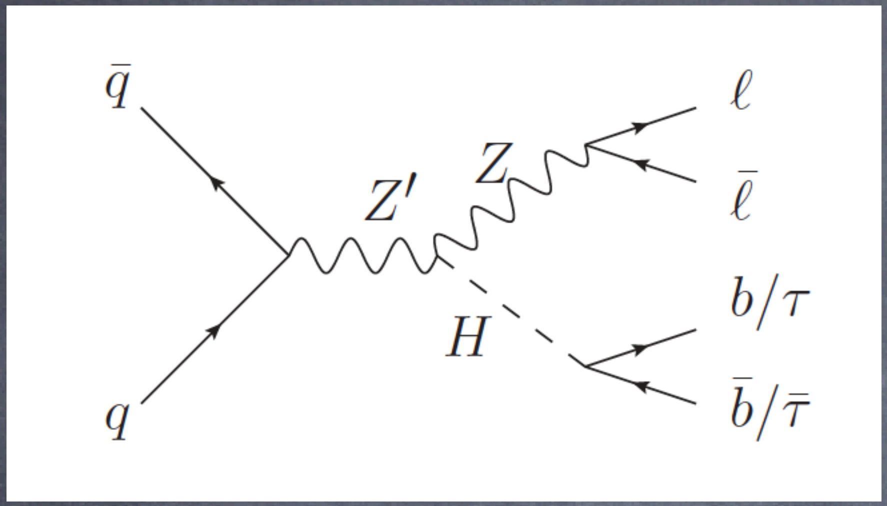


(ex) L=60 fb^{-1} for $M_{Z'}$=600 GeV
[Details omitted]

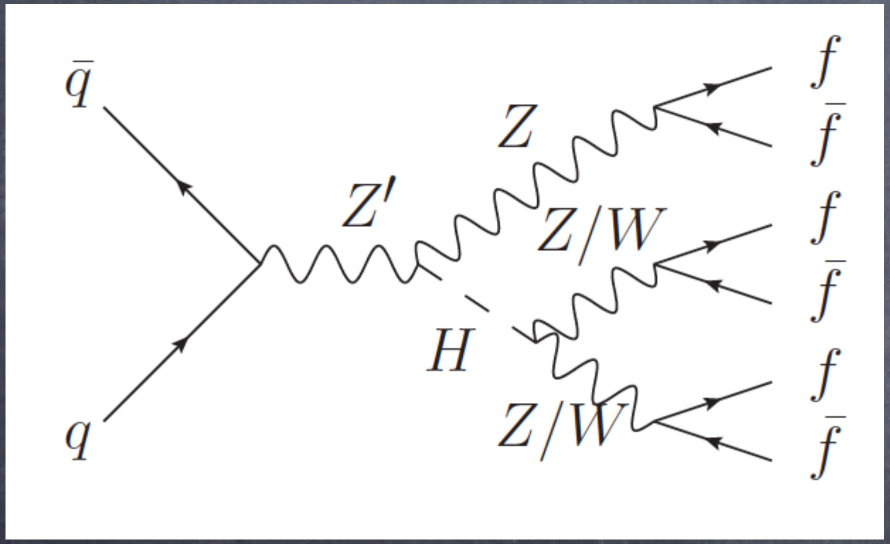
Works for even leptophobic Z'

(iv) More channels for Higgs search

[Works in future]



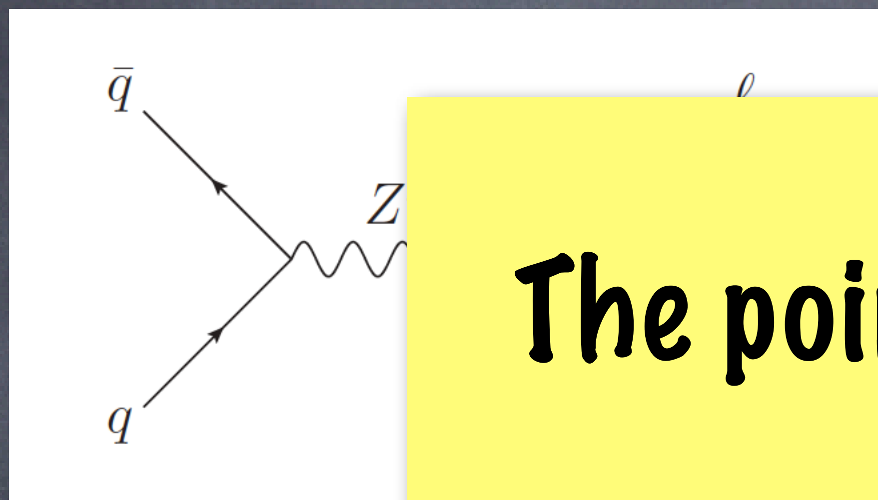
2-lepton + 2b/2τ-jet resonance
: search for a light Higgs



2-lepton + 2Z/2W resonance
: search for a heavy Higgs

(iv) More channels for Higgs search

[Works in future]



resonance
t Higgs

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y Higgs

The point is

New force can help
"Higgs search" at the LHC.

New dark matter candidates in SUSY with a New force

1. New neutralino (Z′-ino) dark matter
   [Barger, Langacker, HL (PLB 2005)]
2. Sneutrino dark matter
   [HL, Matchev, Nasri (PRD 2007)]
3. Hidden sector dark matter
   [HL (PLB 2008)]
4. Multiple dark matters
   [Hur, HL, Nasri (PRD 2008)]

Variety of DM candidates with distinguishable properties in SUSY is possible.

Lightest U-Parity Particle (LUP)
: Hidden sector DM candidate

[no interaction with SM, except through the new U(1)]

$$U(1) \rightarrow Z_6 = Z_3 \times Z_2$$

with $Z_3 = B_3$ (Baryon triality) -> stable proton
$Z_2 = U_2$ (Hidden sector parity) -> stable DM

Without R-parity,
LSP (usual DM candidate) decays,
but LUP (new DM candidate) is stable.

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LUP is a viable DM candidate.
(satisfies all observational constraints)

Summary

(1) New interaction U(1) at TeV scale is well-motivated.

Higgs -> Supersymmetry -> U(1)

(2) Z′ is very likely to be the first discovery at LHC.

Resonance + Clean leptonic signals

(3) Many previous SUSY analysis should be revisited.

Huge research opportunity (7400 papers with Supersymmetry title)

(4) New force is useful to discover other New particles.

Search for Higgs, Supersymmetry early at LHC

Similarity between Physics and Lotto

Physics is **Joyful**. It is like Lotto!

Thank you.